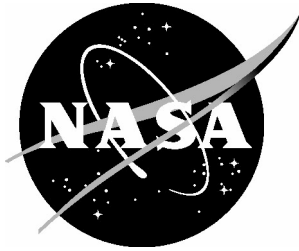


NASA/TM-2005-213544  
ARL-TR-3426



# Effect of Impact Location on the Response of Shuttle Wing Leading Edge Panel 9

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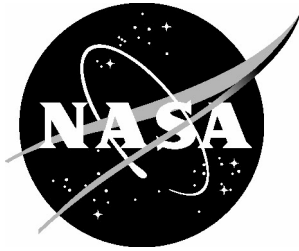
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## Abstract

*The objective of this paper is to compare the results of several simulations performed to determine the worst-case location for a foam impact on the Space Shuttle wing leading edge. These simulations, utilizing the commercial code LS-Dyna, represent the first in a series of parametric studies performed to support the selection of the worst-case impact scenario. Panel 9 was selected for this study to enable comparisons with previous simulations performed during the Columbia Accident Investigation phase. Seven locations spanning the panel surface were impacted with a 5.5-in cube of typical external tank foam weighing 0.23 lb. For each of these cases, the projectile traveled at 1000 ft/s directly aft, along the orbiter X-axis. Results compared from the parametric studies included strains, contact forces, and material energies for various simulations. The results show that the “worst case” impact location was on the top surface, near the apex.*

## Introduction

Following the Space Shuttle Columbia Accident on February 1, 2003, an independent investigation board was formed to determine the cause(s) of the accident. The board delivered Volume I of the final report in August 2003, Ref. [1]. The physical cause of the accident was shown to be the impact of a 1.7 lb piece of external tank foam on the left wing leading edge, see Figure 1. In addition to determining the causes, the Columbia Accident Investigation Board (CAIB) made several recommendations for improving the NASA Space Shuttle Program. Two recommendations directly related to structural impact analysis are:

- Initiate a program designed to increase the Orbiter’s ability to sustain minor debris damage by measures such as improved impact-resistant Reinforced Carbon-Carbon and acreage tiles. This program should determine the actual impact resistance of current materials and the effect of likely debris strikes (Recommendation 3.3-2).
- Develop, validate, and maintain physics-based computer models to evaluate Thermal Protection System damage from debris impacts. These tools should provide realistic and timely estimates of any impact damage from possible debris from any source that may ultimately impact the Orbiter. Establish impact damage thresholds that trigger responsive corrective action, such as on-orbit inspection and repair, when indicated (Recommendation 3.8-2).

An extensive experimental and analytical program was developed to address these recommendations. Specifically, a multi-center analysis team was formed to: 1) use physics-based state-of-the-art codes to simulate debris impacting the Shuttle wing leading edge; 2) validate modeling approaches through test and analysis correlation; and 3) utilize validated modeling approaches to assist in investigating issues not possible to test (e.g., performing parameter studies, simulating additional scenarios, and establishing worst-case scenarios). An overview of the team’s activities during the investigation is documented in Ref. [2]. Related large-scale simulation results are presented in Ref. [3].

The NASA Space Shuttle wing leading edge consists of Panels and T-Seals fabricated from reinforced carbon-carbon (RCC) material. To begin fabrication of a Panel or T-Seal, a precursor woven fabric is layered such that all plies are either in the 0 or 90 degree direction. During the processing, silica is infused in the outer 2-to-3 laminae, and the resulting laminate is heated to form a silicon-carbide coating, see Figure 2. This silicon-carbide coating is necessary to provide protection to the Space Shuttle's leading edge during the high heating experienced on re-entry of the shuttle through the Earth's atmosphere. As shown in Figure 2, the RCC laminate contains many voids. In addition, the process used to create the silicon-carbide causes numerous micro-cracks in the silicon-carbide coating. The porosity and the coating cracks results in material with a highly complex stress-strain and failure behavior.

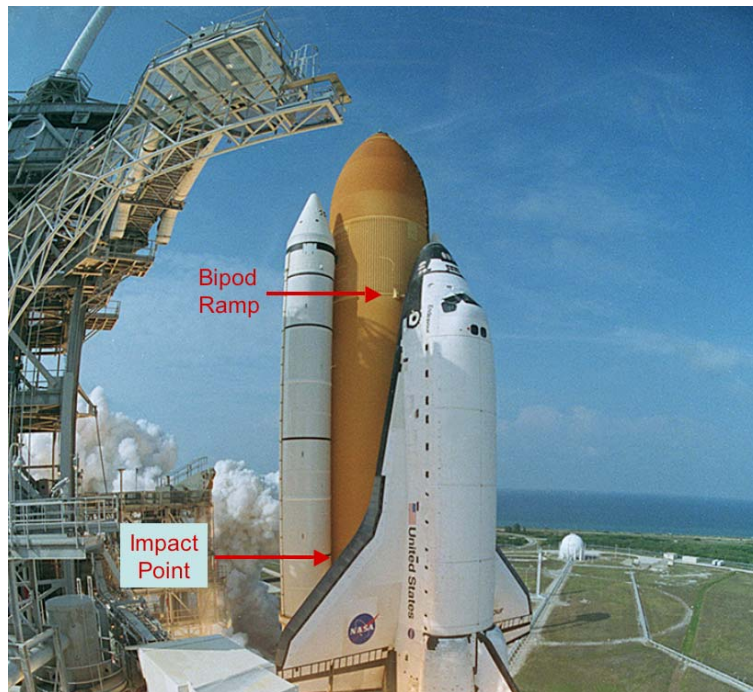


Figure 1. Space Shuttle photograph showing release point of 1.7-lb foam at bipod ramp and the impact point on the left wing leading edge.

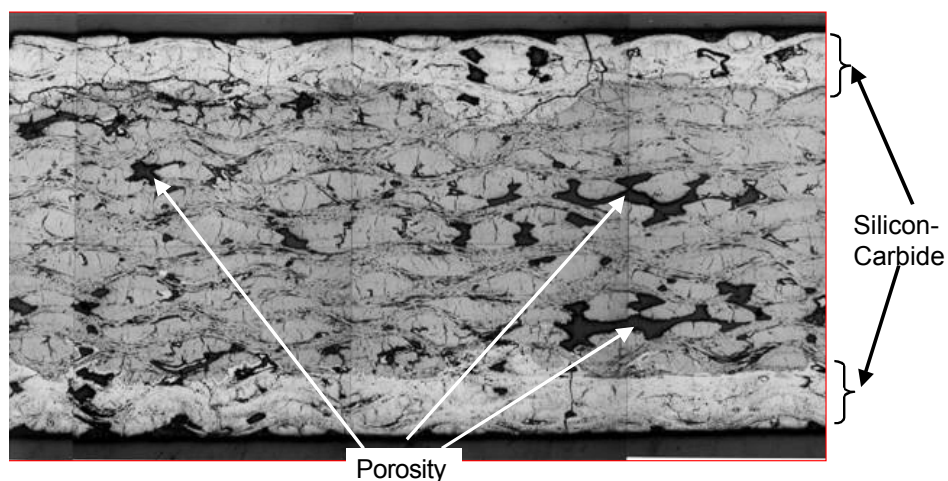


Figure 2. Micro-graph cross-section of RCC material.

The objective of this paper is to compare the results of several simulations performed to determine the worst-case location for a foam impact. These simulations represent the first in a series of parametric studies performed to determine the worst-case impact scenario. The simulations were performed using LS-Dyna, a commercial, non-linear, finite element code, Ref. [4]. Panel 9 was selected for this study to enable comparisons with previous simulations performed during the accident investigation. The projectile for this study is a 5.5-in cube of typical external tank foam. First, the RCC and foam finite element models will be described. Results compared from the parametric studies will include strains, contact forces, and material energies for various simulations.

## Description of Finite Element Model

The RCC panel finite element model was generated from an outer-mold-line (OML) surface geometry for Panel 9. The complete finite element model, including the foam projectiles, is shown in Figures 3 and 4, side view and top view, respectively. Panel 9 was discretized with quadrilateral shell elements having a nominal edge-length of 0.2 inches. The panel consists of 24 parts and 57,414 elements. The panel is fully constrained at the bolt-hole locations.

The panel RCC material properties have been represented in LS-DYNA using MAT #58 (MAT\_LAMINATED\_COMPOSITE\_FABRIC). Detailed information about the development of both the RCC and foam material models can be found in Ref. [5]. The silicon-carbide material comprising the outer layers of the laminate has substantially different material properties, including density, compressive and tensile strengths, etc, than that for the carbon-carbon substrate material. At the time that these studies were performed, the material property information was limited to design data based on **laminated** material testing. For this reason, the material properties change as the number of plies in the laminate change. The RCC also exhibits a wide scatter of failure properties. In addition to the material strength variability, the RCC condition is an important specification. The ‘as-fabricated’ condition refers to the pristine material before subjected to re-entry thermal conditions. The ‘degraded’ material refers to material properties generated from material that had been subjected to ~ 20 to 30 re-entry cycles and resulted in loss of mass and reduction in strength. For these simulations, the RCC material properties were based on average-strength, degraded data. Additional information about the effect of the material variations on the response of a simple RCC specimen can be found in Ref. [6].

The 5.5-inch cubic foam projectiles were represented using 21,700 hexagonal elements with a nominal edge length of 0.2-in. For each case, the foam projectile weighed 0.23 lb and impacted at 1000 ft/s. The foam velocity was oriented directly aft, along the Orbiter X-axis. The foam material properties represent BX250, a foam used on the external tank. Data for the material properties were obtained from static, high-strain rate, and impact tests performed at NASA Langley Research Center and NASA Glenn Research Center. LS-Dyna MAT #83 (MAT\_FU\_CHANG\_FOAM), which can incorporate strain-rate effects, was selected for the foam material implementation. The numbers on the foam projectiles, in Figures 3 and 4, refer to impact locations, where **2** is the apex, **4**, **6**, and **11** refer to lower surface impacts and **104**, **106**, **111** refer to upper surface impacts. The foam was targeted using the point of first contact. The foam orientation did not change as a function of impact location, since the foam projectile was simply translated. However, because of the curvature of the RCC panel, the foam incidence angle varied substantially from location to location.

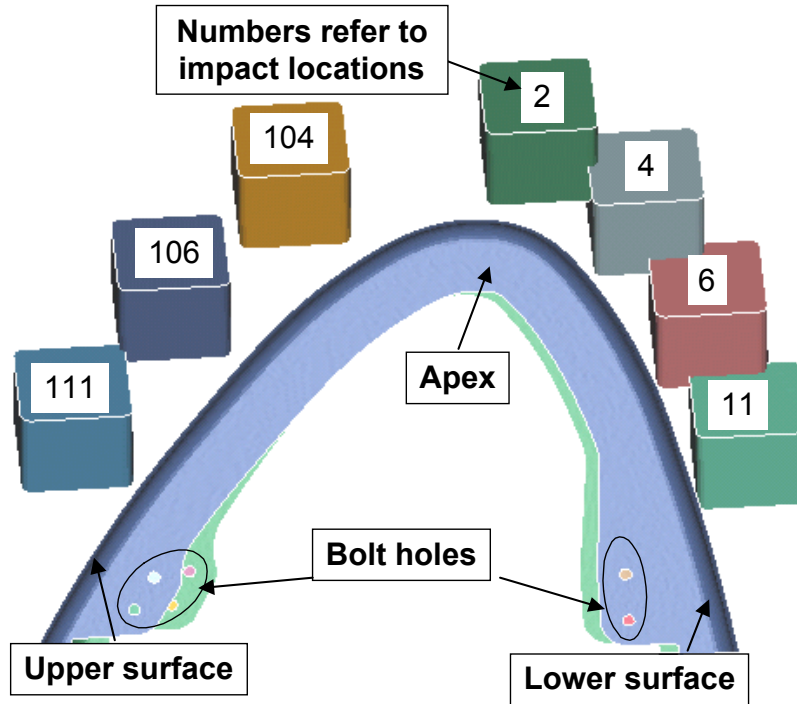


Figure 3. Side view of RCC Panel 9 showing numbered foam impact locations.

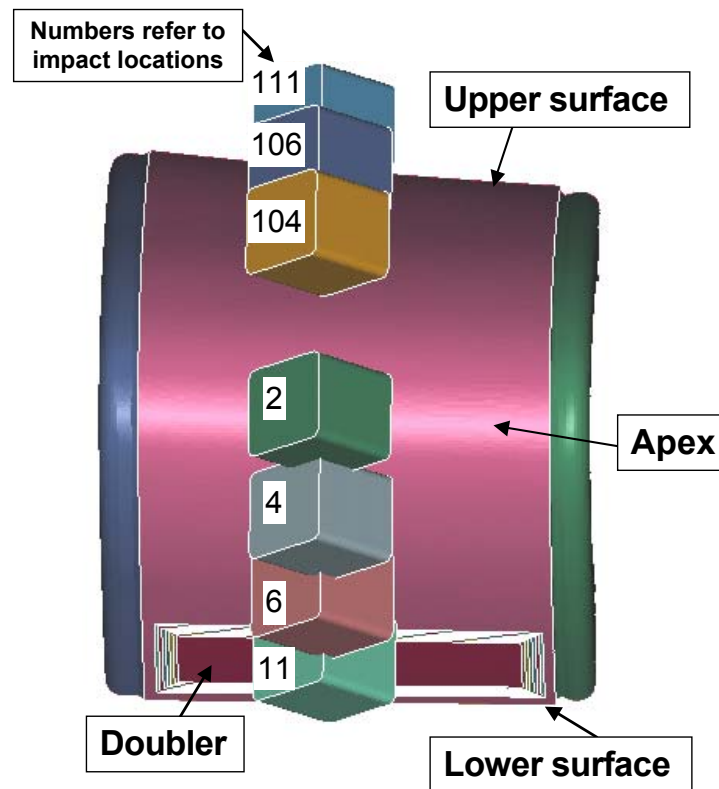


Figure 4. Top view of Panel 9 showing numbered foam impact locations.



## Discussion of Results

A study performed in August 2003, as part of the accident investigation, showed that an impact on the apex was more severe than a lower surface impact. This conclusion was based on a comparison of the impacts of the 5.5-in cube of foam as shown for Locations **2**, **4**, **6**, and **11**. First-principal strain contours for an impact at the apex, Location **2**, are shown in Figure 5. Significant damage commences when the 1<sup>st</sup>-principal strain reaches 0.006. Although a few elements show a high strain level, the impact is relatively benign. Strain contours for lower surface impacts were not shown because they are significantly less, and resulted in no discernable damage to the panel.

Significant damage was evident for the upper surface impacts, see Figure 6. The maximum strain reaches 0.006 for all of the upper surface impacts. The time of the maximum strain has also been noted for each impact. Of particular interest are the results for impact Location **104** where several cracks have been formed. For the Location **106** impact, large strains are shown on the panel face.

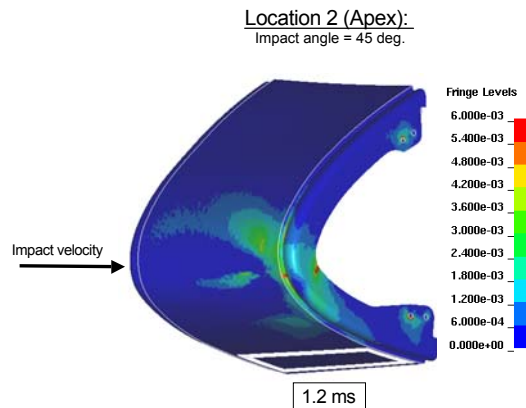


Figure 5. 1<sup>st</sup> principal strain for Location 2

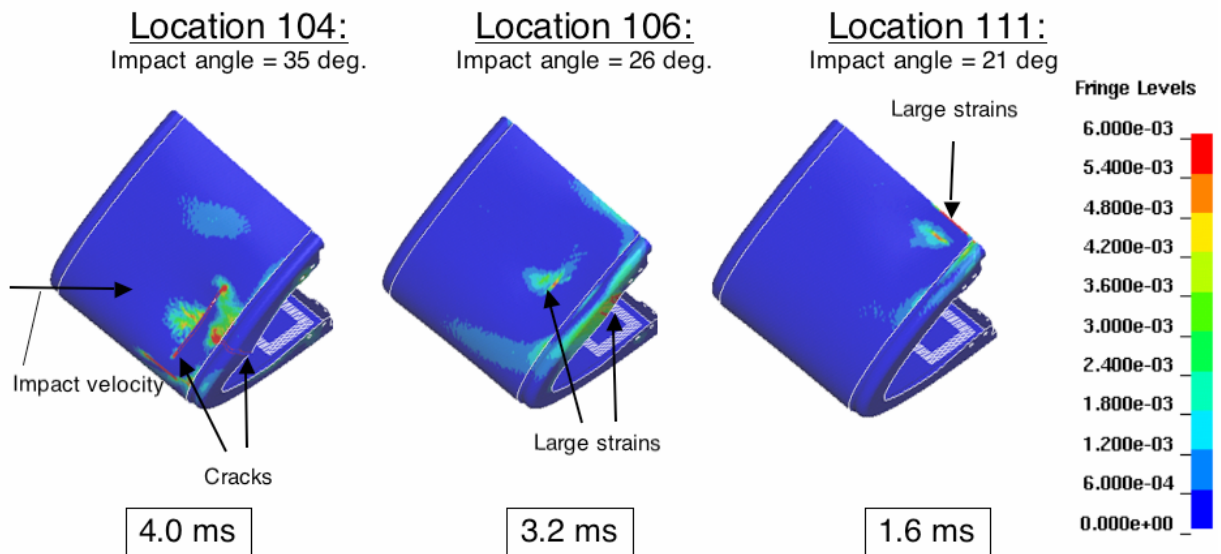


Figure 6. 1<sup>st</sup> principal strain for upper surface impact locations

The contact force time-history for each of the impacts is shown in Figure 7. The contact force is the force generated within the computer code that prevents the foam from penetrating the RCC panel and thus represents the force imparted to the panel. In general, the contact force is dependent on several factors including the material properties, impact angle, velocity, structural stiffness, etc. For the impacts considered here, the contact force variations are strongly dependent on the relative impact angle and RCC structural stiffness. The impact angle is defined as the angle between the foam velocity vector and a tangent plane to the RCC surface at the impact point. For these impacts, the impact angle ranges from nearly 45-degrees at the apex, to less than 11-degrees for an impact at Location **11**. Table I contains the maximum contact force, impulse, and impact angle as a function of impact location. The impulse is computed by integrating the contact force over time. The overall maximum force and the largest impulse are for the apex impact, Location **2**. However, because of the relatively stiff structure (the apex is highly curved), the resulting deformation and damage is considerably less than for a Location **104** impact.

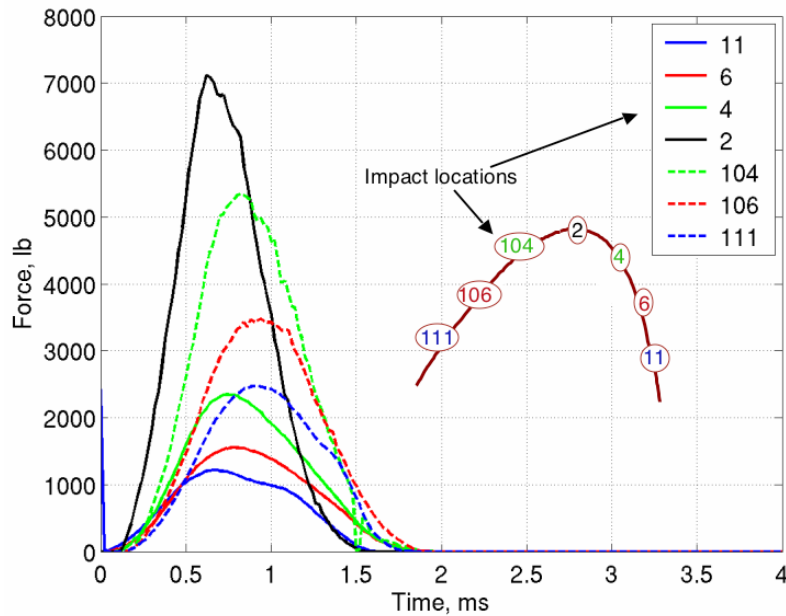


Figure 7. Contact force time histories for various impact locations.

Table I. Force, impulse and impact angle for various impact locations.

Impact Location	Maximum Resultant Force, lb.	Impulse, lb.-s	Impact angle, degrees
11	1100	1.1	11
6	1500	1.4	13
4	2400	2.0	22
2 (apex)	7000	4.4	45
104	5300	4.0	35
106	3400	2.9	26
111	2500	2.1	21

In addition to the contact forces, the RCC and foam energies provide additional insight about the panel responses. The RCC panel kinetic energy varies substantially as a function of response location, see Figure 8. The upper surface impacts produce significantly more panel motion than the lower surface impacts. This can be related to the impact angle and the absence of a “doubler” region on the upper surface. This doubler region stiffens the lower surface and thus inhibits global deformations.

The RCC panel internal energy also varies as a function of impact location, see Figure 9. The

internal energy is the stored strain energy that is generated by the bending deformation of the panel. As would be expected based on the kinetic energies, the internal energy is largest for the Location **104** impact. The upper surface impacts have more deformation and therefore more internal energy. Although the apex had the largest contact force and impulse, the panel response was less than either Locations **104** or **106**. This difference in trend results from the difference in structural stiffness that is determined by the relative curvature.

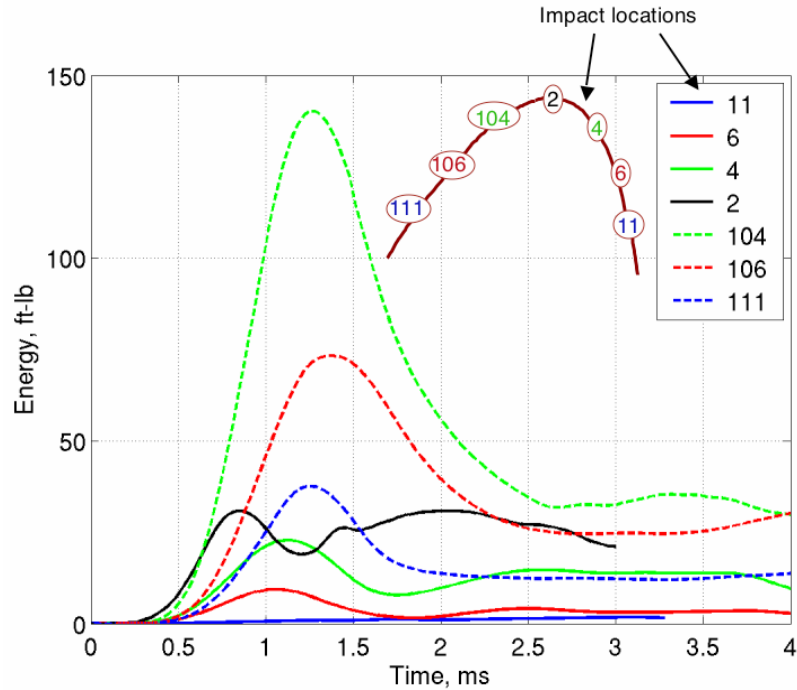


Figure 8. RCC face kinetic energy time histories for various impact locations.

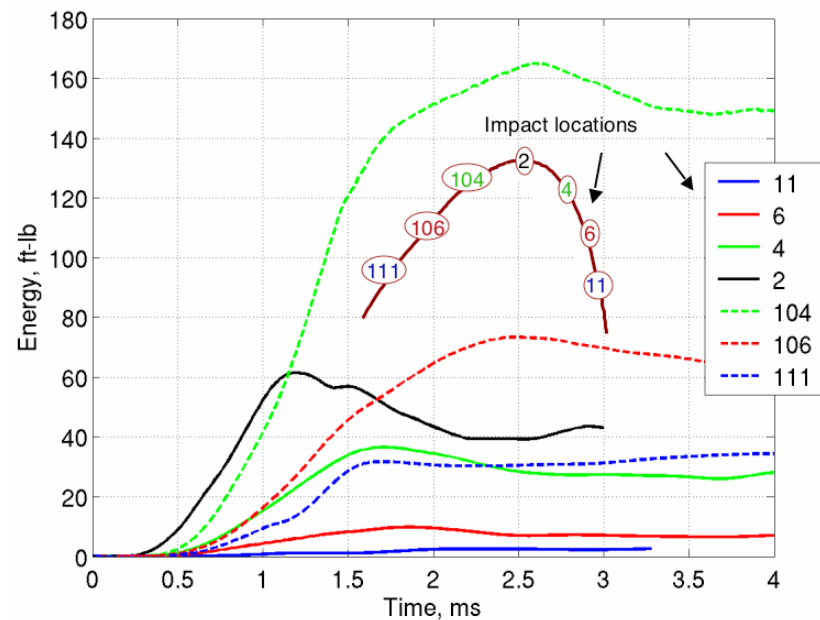


Figure 9. RCC face internal energy time histories for various impact locations.

The foam kinetic and internal energies are shown in Figures 10 and 11, respectively. The reduction in kinetic energy of the foam can be directly related to the angle of impact. Thus the most kinetic energy of the foam is removed for the apex impact, Location **2**, while the least kinetic energy is removed for Location **11** on the lower surface where the impact angle is glancing. The foam internal energies, see Figure 11, show two distinct response types. For the upper surface, apex, as well as Location **4** on the lower surface, the internal energy of the foam is similar in magnitude and time history shape. For Locations **6** and **11** on the lower surface, the foam internal energy is considerably less. Thus the foam for impacts at Locations **6** and **11** is much less crushed during the impact.

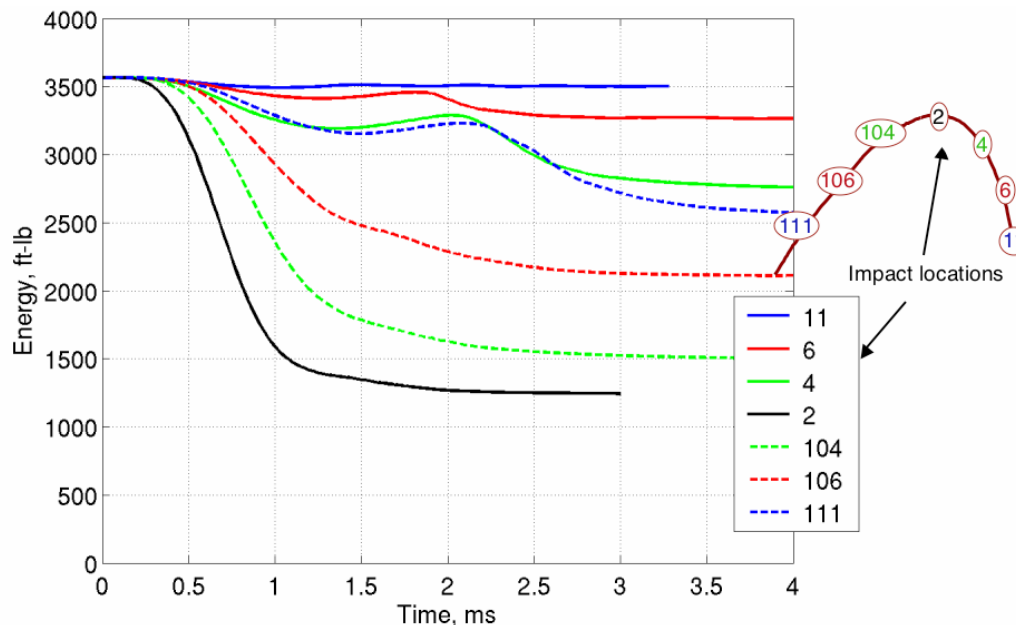


Figure 10. Foam kinetic energy time histories for various impact locations.

## Concluding Remarks:

Simulations of foam projectiles impacting a representative Space Shuttle wing leading edge panel were presented. Specifically, seven locations spanning the Panel 9 surface were impacted with a 5.5-in BX-250 foam cube weighing 0.23 lb. For each of these cases, the foam was traveling directly aft, along the orbiter X-axis, at 1000 ft/s. A detailed comparison of the results has been included. The evaluations were based on panel strains, foam and RCC energies, and the contact force. Since the orientation of the cube was not changed with respect to the global coordinate system, the results show the combined effect of both angle of incidence and panel geometry on the response. For this parameter study only the impact for Location **104** produced a visible hole in the panel. The results show that the “worst case” was Location **104** - on the top surface near the apex.

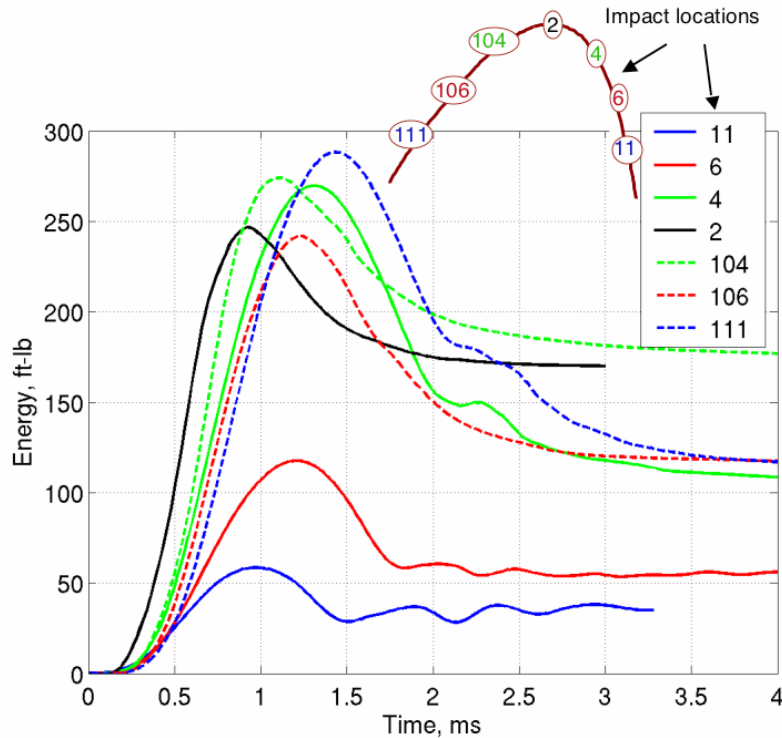


Figure 11. Foam internal energy time histories for various impact locations.

## References:

1. Gehman, H. W., *et al*: Columbia Accident Investigation Board Final Report Volume I. U. S. Government Printing Office, Washington DC, 20402-0001, August 2003.
2. Melis, M; Carney, K; Gabrys, J.; Fasanella, E.; and Lyle, K.: A Summary of the Space Shuttle Columbia Tragedy and the Use of LS-DYNA in the Accident Investigation and Return to Flight Efforts. Proceedings of 8<sup>th</sup> International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.
3. Fasanella, E.; Lyle, K.; Gabrys, J.; Melis, M.; and Carney, K.: Test and Analysis Correlation of Foam Impact onto Space Shuttle Wing Leading Edge RCC Panel 8. Proceedings of 8<sup>th</sup> International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.
4. LS-DYNA Keyword User's Manual (Version 970), Livermore Software Technology Corporation, Livermore CA 94551, April 2003.
5. Carney, K.; Melis, M.; Fasanella, E.; Lyle, K.; Gabrys, J.: Material Modeling of Space Shuttle Leading Edge and External Tank Materials for Use in the Columbia Accident Investigation. Proceedings of 8<sup>th</sup> International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.
6. Lyle, K.; Fasanella E.; Melis, M.; Carney, K.; Gabrys, J.: Application of Non-deterministic Methods to Assess Modeling Uncertainties for Reinforced Carbon-Carbon Debris Impacts. Proceedings of 8<sup>th</sup> International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.

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